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Resonant tunneling diodes based on stacked self-assembled Ge/Si islands

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Abstract. We present a new concept and first results of resonant tunneling diodes based on self-assembled Ge/Si islands. The proposed structure consists of closely stacked and vertically aligned Ge islands which create vertical channels with energetically deep thermalization layers and high Si double barriers for holes in the valence band. The current–voltage (I–V) curve of such a layer sequence shows two resonances which we attribute to the heavy-heavy hole and heavy-light hole (lh) transition. The lh resonance is pronounced and negative differential resistence is conserved up to over 45 K. Magnetic field dependence of the resonances suggest that the tunneling current through the structure is of 2-dimensional character.

Introduction

Self-assembled Ge/Si islands have been of broad interest during the last years and much effort has been put into their structural [1–5], vibrational [6] and electronic investigation [7–9]. Despite the large effort to understand their fundamental properties, devices incorporating Ge/Si islands as active material are only scarcely found. RTDs with SiGe/Si quantum wells are commonly found in the literature [10, 11]. However, their preformance is rather poor, yielding negative differential resistence only up to moderate temperatures around 150 K. Valence band (VB) offsets of typical RTDs are about 200 meV (Ge concentrations of 20%) and thermal quenching plays a major role at higher temperatures. In this contribution we propose a new concept for resonant tunneling diodes (RTDs) which makes use of self-assembled Ge islands. The purpose of the concept is two-fold: First, the large valence band offsets of Ge islands are used to create deep Ge rich vertical channels with high Si double barriers. Second, vertically and self-aligned Ge/Si island stacks offer the possibility of perfect side passivation.

1. Results and discussion

Figure 1(a) shows a cross-section transmission electron microscopy (TEM) image of a typical active layer arrangement in quantum well RTDs. Two thick $Si_{1-x}Ge_x$ quantum wells at the bottom and the top serve as thermalization layers for holes. The double barriers are created by a thin $Si_{1-x}Ge_x$ quantum well sandwiched between two Si barriers. The schematic band edge alignment for the VB is given next to the TEM image.

A new concept is presented in Fig. 1(b).

It is based on the vertical self-alignment of closely stacked Ge/Si islands, as has been investigated in detail in the literature [4, 5]. In this case the thermalization layers are created by very closely stacked Ge islands yielding small minibands due to strong electronic carrier

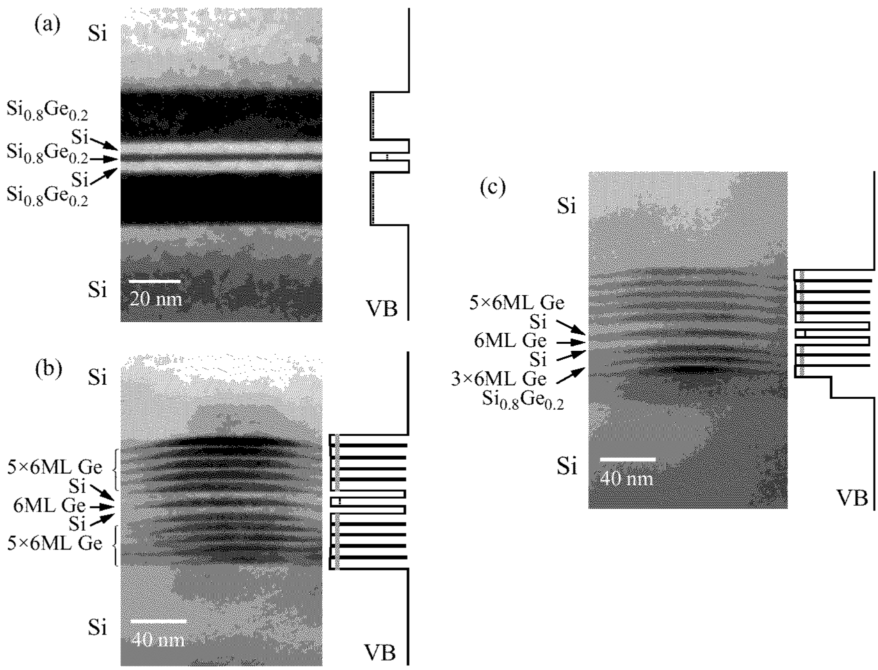

Fig. 1. Cross-section TEM images illustrating three different approaches to realize resonant tunnelling diodes based on the SiGe material system. Schematic band-alignment without doping and bias is shown next to the TEM images. (a) shows the conventional quantum well case, whereas in (b) and (c) Ge islands are used for the thermalization layers and the resonant tunneling structure.

coupling. The two Si barriers are formed by leaving a slightly thicker spacer layer between the 5-th and 6-th as well as the 6-th and 7-th island layer. The schematic band edge alignment (without bias and doping) yields much larger valence band offsets than for the quantum well case. A slight modification of this concept can be found in Fig. 1(c), where the first two island layers are substituted by a thick SiGe quantum well.

2. Samples and experimental setup

We concentrate our investigation on one sample which was grown by solid source molecular beam epitaxy. The exact growth procedure follows the concept of Fig. 1(c): On a p^+ Si (001) substrate a 100 nm Si:B (1×10^{19}) layer is grown followed by a 12 nm thick $Si_{0.82}Ge_{0.12}$ quantum well. After that a stack of 4 bilayers of 6 ML Ge and Si layers is deposited, where the Si spacer layer between the 1-st and 2-nd island layer is 9 nm and all other Si spacers are only 5 nm thick. The structure is finished with a 150 nm thick Si:B (1×10^{19}) cap. The growth temperature for the Ge islands was 600 °, resulting in low density and large dome-like Ge islands with diameters of about 80 nm [7]. A schematic of the layer sequence is given as an inset in Fig. 2. The sample is then processed into mesas (∼300 nm wide) using optical lithography and wet-chemical etching. For such diameters we expect less than 5 island stacks in the mesa. Electrical measurements are carried out in a ^{3}He evaporation cryostat equipped with a 12 T magnet.

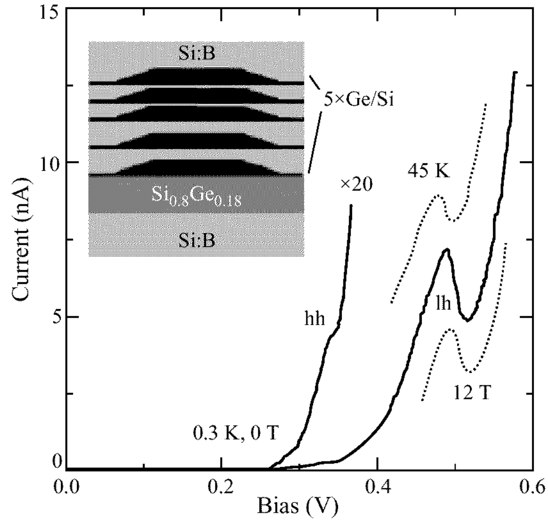

Fig. 2. The I–V curves of the RTD at 0.3 K and no magnetic field (solid line), at 12 T (lower dotted curve) and at 45 K with zero magnetic field (upper dotted curve) are shown. The dotted lines are shifted in vertical direction for clarity. The inset shows a schematic of the RTD.

3. Electrical characterisation and discussion

The I–V curve of the RTD is presented in Fig. 2 (solid curve) and shows two resonances, one at 0.49 V, which exhibits negative differential resistance (NDR) and a second shoulder at about 0.34 V. The two features can be explained by resonant tunnelling through the hh and lh subbands of the middle Ge island. In fact, the I–V characteristic looks very similar to what has been observed for conventional RTDs using Si/SiGe quantum wells [10]. The similarity between our island and the QW RTDs suggests a 2D density of states in the Ge islands. This is a reasonable assumption since the lateral extension of these islands is much larger than the de-Broglie wavelength of charge carriers. Figure 2 also shows (upper dotted curve) that NDR is conserved up to 45 K. Information about the dimensionality of the tunneling structure can be obtained by magnetic field dependences of the resonant current peaks. The I–V curve for a magnetic field $B = 12$ T parallel to the current is also given in Fig. 2. It is striking that only a minor voltage shift of about 4 mV is observed for the resonance at 0.49 V. This is characteristic for 2D structures and in clear contrast to a 0D quantum dot, where we would expect a pronounced shift of the resonance peak with increasing magnetic field.

Although our first results look very promising we want to address some problems faced during the fabrication of such RTDs. Recently, we showed that the degree of material intermixing in upper layers is more pronounced [9]. Additionally, penetrating strain fields and different island sizes are likely to modify the electronic band structure in the island stacks and in the sandwiched Si barriers. All these effects make it very difficult to produce vertically homogeneous islands and hence to evaluate the exact band edge alignment. On the other hand, it is well known from QW RTDs that a careful tuning of the band edge alignment is essential to obtain good device performance. Hence, the fundamental electronic properties of Ge/Si island stacks need to be investigated further to improve the promising RTD results presented in this paper.

4. Conclusion

In conclusion, we have introduced a new concept to fabricate RTDs based on stacked Ge/Si islands. The concept exploits the effect of vertical self-alignment and creates vertical Ge channels with larger valence band offsets than in conventional Si/SiGe quantum well RTDs. A first sample shows pronounced resonance peaks in the I–V curve, which are attributed to the hh and lh resonant tunneling currents. The lh resonance is distinct and exhibits negative differential resistence for temperatures larger than 45 K. Magnetic field dependent measurements suggest a 2D density of states in the Ge islands. Problems in the fabrication of homogeneous islands are addressed.

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